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TITLE: THE LASERTRON RF GENERATOR FOR FEL APPLICATIONS

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THE LASERTRON RF GENERATOR FOR FEL APPLICATIONS*

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The lasertron rf generator uses an rf-modulated laser beam to generate a tightly bunched electron beam that is accelerated by a dc power supply to the fractional megawatt region. The tightly bunched beam then crosses an output cavity where most of the kinetic energy may be extracted. The bunching is so good that efficient microwave generation at 3 GHz and above is feasible, and three projects worldwide are under way for these frequencies. All three existing projects focus on the linear collider application of high peak power with good efficiency, short output pulses, and low average power. A short review of these projects is presented.

The main thrust of this paper is to discuss the lasertron as the rf generator for free-electron laser (FEL) rf systems. The author has developed a ring model of the lasertron device that shows excellent dc-to-rf conversion efficiency at high output power over the 400- to 1700-MHz frequency range. The issue of the lasertron advantages at higher average output power is also explored. First-order estimates of the weight versus frequency and power are also made. An outline of an experiment that uses the Los Alamos photoinjector to make a lasertron is also presented.

1. Introduction

The lasertron is an energy converter that transforms dc electrical and laser optical power into microwave power. The mechanism for the conversion process is a bunched electron beam, which is produced at a photocathode by an rf-modulated laser. The major parts of the lasertron [1,2] are the laser system, the photocathode, the dc acceleration gap, and the output cavity as shown in fig. 1. The lasertron output cavity operates much like a klystron, except the beam is produced already bunched at the photocathode rather than having the bunches produced by velocity modulation. The advantages of the lasertron stem from the fact that it is possible to

produce a tighter bunch with the laser than with conventional bunchers. One advantage is that the pulsed-power modulator for the lasertron may not be required, and this system is often more complex, expensive, and heavy than the rest of the rf system. A disadvantage is that the beam continuously debunches along its path from the cathode to the output cavity, under the influence of space charge. The space-charge forces always act to accelerate the front of the bunch and decelerate the rear; hence, the only method to reduce the space-charge spreading is to reduce the transit time from the cathode to the center of the output cavity. But the transit time is limited by the maximum obtainable gradient in the dc gun, and the maximum gradient without sparking depends only on the gun design, materials, and the temporal duration of the dc beam voltage. Because one of the major advantages of the lasertron is the elimination of the pulsed-power modulator, the temporal duration of the high voltage is very long, and dc values of the sparking gradient in the gun region must be used.

The photocathode and the laser system may be made in several ways, but the mode-locked laser and Cs_3Sb photocathode of Fraser, Sheffield et al. [3] have produced the best experimental results to date. A block diagram of the mode-locked laser system is also shown in fig. 1. A 10-W cw Nd:YAG laser at 1064 nm is the optical source. A cavity mode-locked laser is driven at 54.17 MHz to produce a micropulse train at 108.33 MHz. A Pockels cell gates the pulse train, producing a macropulse burst of up to 20 µs in length at a 1- to 5-Hz repetition rate. The macropulse is amplified by a factor of up to 1000, resulting in a peak power of up to 1 MW in the micropulses. The rf repetition rate of the pulses is then multiplied by a spatial multiplier to the desired rf frequency. The multiplier losses are made up by another amplifier stage, if required. The beam is then focused onto a potassium dideuterium phosphate (KDP) crystal that halves the wavelength with an efficiency of 50%. The emerging green light at 532 nm is filtered and sent to the photocathode.

2. Calculated results

The author has recently written a ring model computer code of the lasertron interaction [2,4], and his colleagues have published an informal report [5] with some calculation results using this code. The ring model code follows the electrons from the photocathode, through an acceleration gap, through an output cavity, to a collector, with time as the independent variable. The model is fairly complete, with

relativity, space-charge forces, external focus fields, time-varying laser pulses, and many other effects included [4,5]. The major disadvantage of the model is that only the steady-state response is calculated, so all transient processes are ignored. The inputs to the code are the lasertron geometry, the external focus fields, the time history of the laser pulse, and many variables concerning the detail of the calculation methods, the cathode current or charge, voltages and phases, etc. The outputs are the electron trajectories, dc-to-rf conversion efficiency, output power, and many detailed variables used mostly for diagnostic purposes. A series of calculations was performed with a gun gradient of 100 kV/cm, which is a high value for a dc gun, versus frequency. A planar gun and output gap field was assumed to minimize the number of geometric inputs required. A linear focus field with break points at the cathode and at the center of the output cavity was used. For each beam voltage, a four-parameter search was made on the output cavity voltage, phase, the focus field at the output cavity, and the focus field at the cathode. The maximum efficiency was found with this search. The frequency of operation was varied, but the beam size, output gap length, and distance between the anode and the gap center were kept constant in terms of the operating wavelength. The fraction of the maximum possible extracted charge was also kept constant, and the rectangular laser light pulse was scaled as a constant fraction of the rf period. The results are plotted in fig. 2. The lasertron is seen to be an efficient generator of microwaves, especially at frequencies below 2 GHz. At higher frequencies, the klystron can be designed for better bunching and higher efficiencies than the lasertron. The lasertron does not use transit time to improve the bunching; hence, it functions more like a microwave triode, and the performance drops off sharply with frequency.

3. Summary of experimental programs

Several experimental lasertron projects are being pursued all over the world. The oldest experiment is at the Stanford Linear Accelerator Center (SLAC), where a 6-GHz lasertron with a 400-kV, 125-A beam is being built and tested. The microwave-modulated laser system has been the biggest problem to date, and serious rf testing has been held up by the laser. This lasertron will use a high-efficiency GaAs photocathode, and quantum efficiencies of above 10% have been measured at SLAC with nanosecond laser pulses. The lasertron has withstood the full 400 kV with no beam, and the initial tests with a nanosecond laser have resulted in

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breakdown of the gun region at about 120 kV* and the major problem is thought to be cesium contamination of the electron gun insulator.

The lasertron at the Japanese National Laboratory for High Energy Physics (KEK) has been operated at 150 kV and produced 80 kW of output power at 2856 MHz. The dc-to-rf conversion efficiency is only 2.5%, rather than above 50% that is expected. The KEK experiment also uses the GaAs photocathode, and the quantum efficiency is between 2 and 5%. The low dc-to-rf conversion efficiency may be due to the slow time response of the photocurrent in the semiconducting cathode [6]. The next phase of the experiment is to run the lasertron up to 250 kV, which will essentially eliminate space charge as a factor in the device's efficiency.

Another experimental lasertron program is at the Linear Accelerator Laboratory (LAL) at the University of Paris-South in Orsay, France, where the author spent a sabbatical year developing the ring model code. The LAL lasertron will operate at 6 GHz and it should produce 25 MW of output power at 70% dc-to-rf conversion efficiency [5]. It will operate at 400 kV, and the choice of cathode has not yet been made. Three types of cathodes, Cs_3Sb, GaAs, and arrays of photo-assisted field emitters are being considered. The dc external energy storage system and the experimental vacuum enclosure have been built, and rf experiments should be under way in early 1988.

The three above projects all employ 100- to 1000-ns-long macropulses and are directed toward producing very short, intense bursts of microwaves for future linear colliders. However, for high average power FELs, a much lower peak output power is required, but at pulse lengths from the few to hundreds of seconds. Even continuous wave rf systems may be required for the highest average power FELs. An experimental project to demonstrate the long pulse operation of the lasertron is being started at Los Alamos. The photoinjector system of Fraser and Sheffield is being modified to include an output cavity, as shown in fig. 3. The laser system will be modified with a 4-times pulse multiplier and an additional amplifier to produce a 433-MHz optical pulse train at up to 20 μs length. The photoinjector can produce 3-A current averaged over a macropulse at 1 MeV, and the first experiments will utilize this 3-MW beam power to obtain 1.5 to 2 MW of rf power. The most serious experimental problem at both SLAC and KEK has been cesium contamination of the ceramic in the gun. The Los Alamos experiment solves the cesium problem by

*J. Weaver, Stanford Linear Accelerator Center, private communication, May 1987.

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fabricating the photocathode in a separate, valved-off section of the vacuum system, and the rf injector uses no insulators. Later versions of the experiment will use dc rather than rf energy to produce the beam.

4. Lasertron weight and size scaling

The lasertron requires only a single rf cavity, rather than the four or five cavities that the klystron uses. This weight savings is reduced by the weight required for the laser system, which is a function of the average and peak optical power. The collector and electron gun portions of the two generators are very similar, and the magnetic field requirements are also similar, but the total length of magnetic field required in the lasertron case is reduced. Thus, the author's previous estimates of klystron weight [7] may be modified and used for the lasertron, provided that the laser component is added. Comparing the lasertron to the klystron, one sees that the lasertron has about 25% of the klystron's rf length (because of one cavity instead of four or five), and the lasertron's electron gun is lighter by about 20% because of the lack of a heater and a heat shield system. The lasertron does have a laser system, which weighs

$$W_{laser} = 15(1 + f/3 \times 10^9). \tag{1}$$

Using the above fractions applied to the author's previous estimates for klystron weight [7], one finds an expression for the lasertron weight as follows:

$$W_{lasertron} = 8.4 \times 10^7 \, V_0^{1/2}/f + 4 \times 10^{-5} \, V_0 + 1.0 \times 10^{19}/f^2 + 14.4 \, (V_0 I_0)^{0.7344}$$
$$+ \, 15 \, (1 + f/3 \times 10^9). \tag{2}$$

The equation units are mks. As an example, a 500-kW klystron at 450 MHz would weigh 347 kg, and the lasertron would weight 280 kg. In both cases the power supplies and cooling systems are neglected and must be estimated separately.

5. Conclusions

The lasertron has the potential for being a highly efficient, lightweight microwave generator for many applications in accelerator technology, including the FEL application. The major uncertainties for the use of the lasertron are the cathode life and cesium contamination issues, both of which can only be resolved by experimental programs. There are several experimental programs now under way to attempt to answer these questions.

6. Acknowledgments

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Figure Titles

Fig. 1. Schematic of the lasertron and the rf-modulated laser.

Fig. 2. Calculated conversion efficiency versus frequency for the lasertron.

Fig. 3. Drawing of the Los Alamos lasertron experiment.
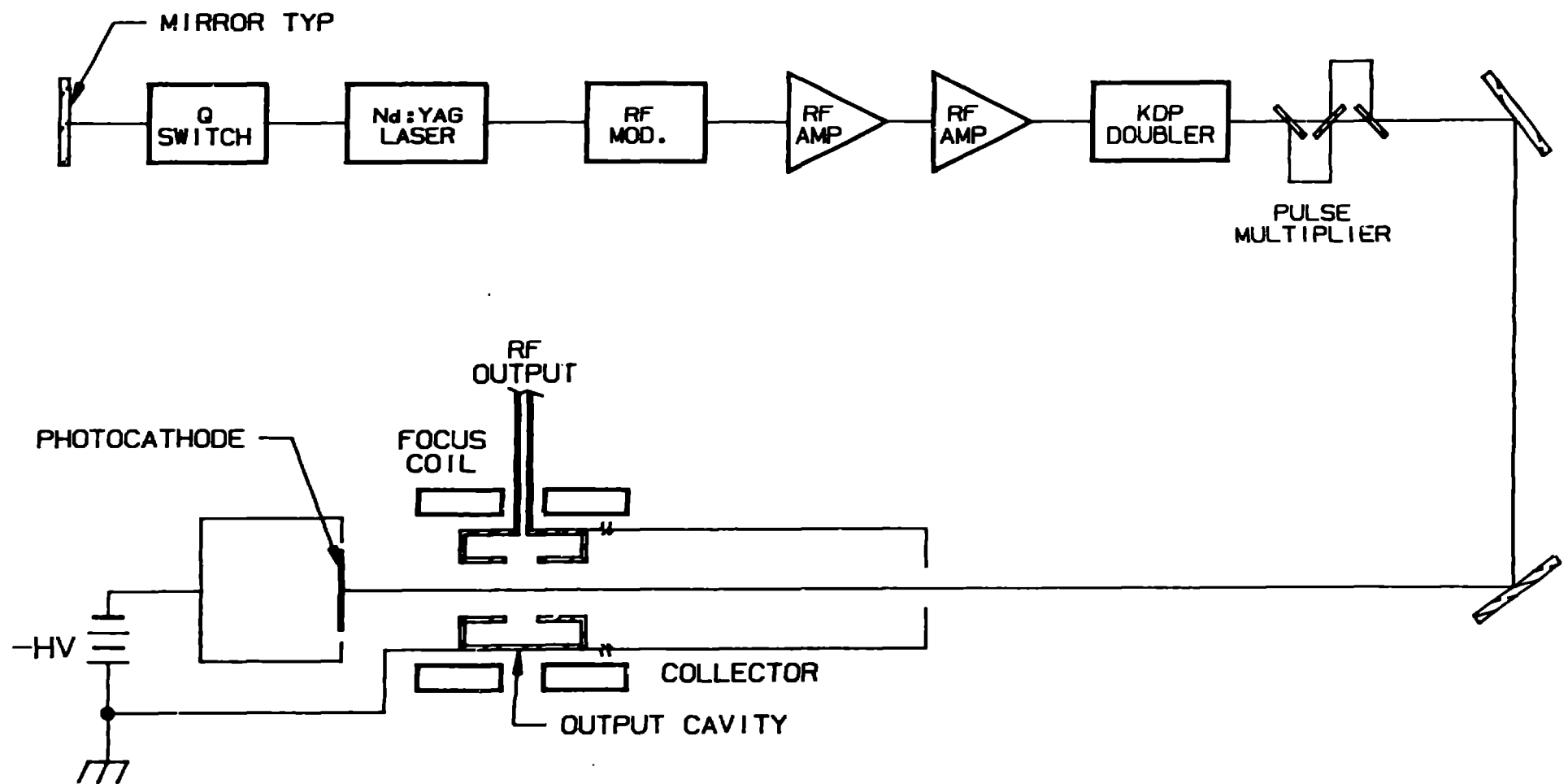
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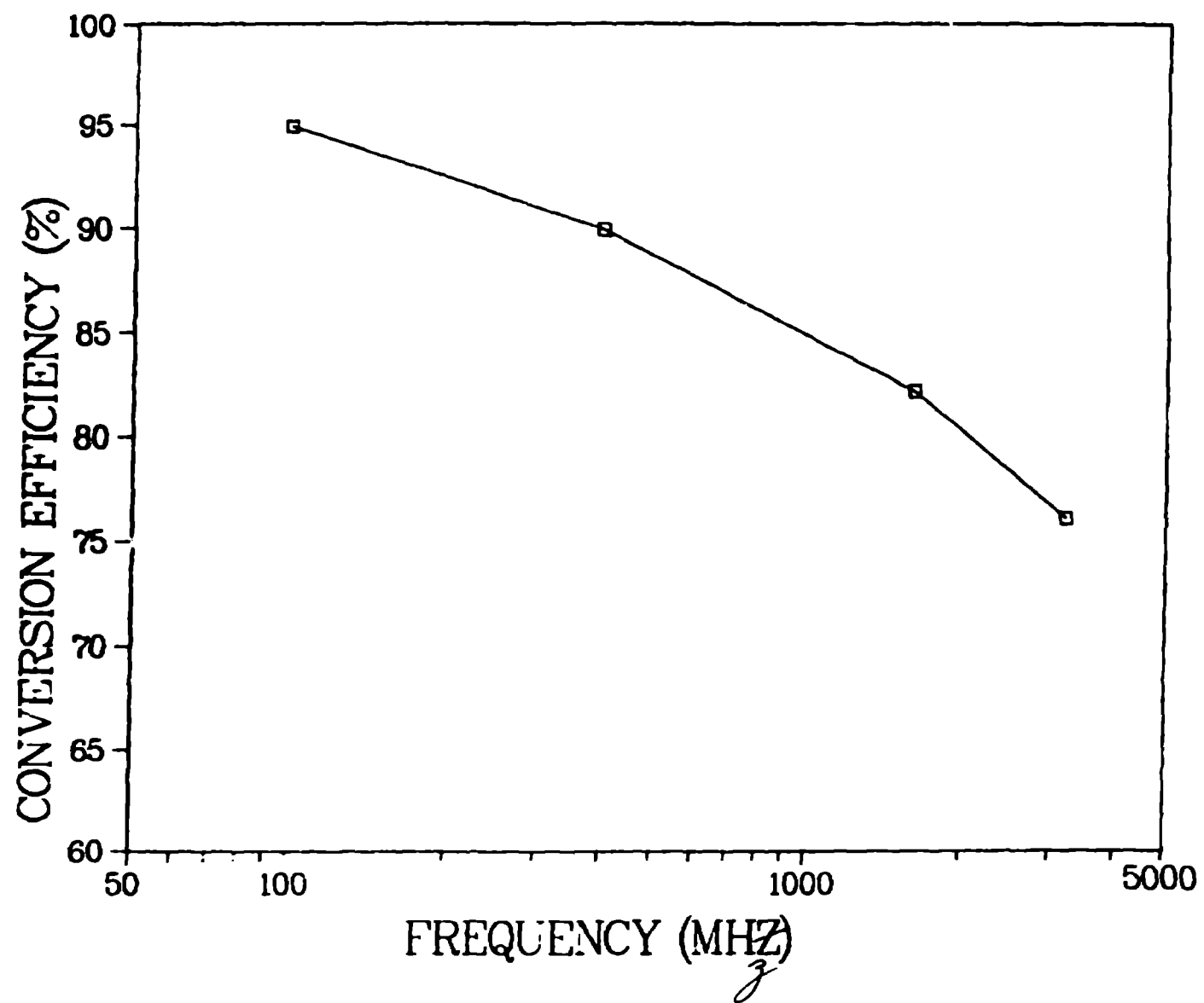(to correct orig. fig.)
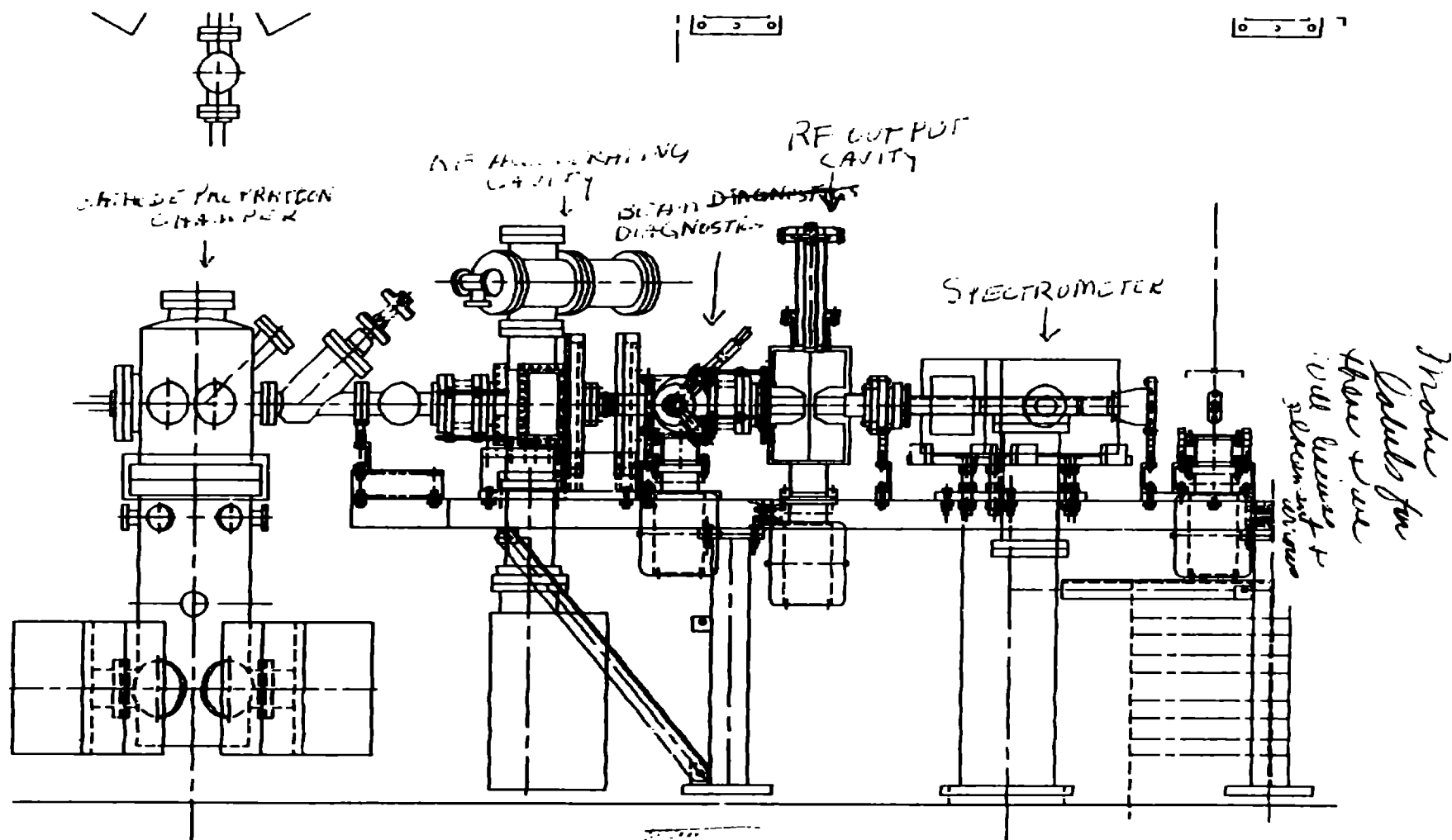
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RF OUTPUT

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FOCUS COIL

−HV

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